NSTC COMMITTEE ON TECHNOLOGY
SUBCOMMITTEE ON NANOSCALE SCIENCE, ENGINEERING, AND TECHNOLOGY

National Nanotechnology Initiative Signature Initiative:

Sustainable Nanomanufacturing – Creating the Industries of the Future

February 2010

Collaborating Agencies[1]: *NIST*, *NSF*, *DOE*, *EPA*, *NIH*

National Need Addressed

This interagency initiative will establish manufacturing methods for economical and sustainable integration of nanoscale building blocks into complex, large-scale systems.

A decade of research under the National Nanotechnology Initiative has led to remarkable discoveries of nanoscale materials with unique properties, laboratory demonstrations of a range of innovative nanoscale devices, and introduction of limited number of nanotechnology-based products into the marketplace. For this investment to become the basis for high-value industries, methods must be established to efficiently assemble products that integrate together billions or more of nanoscale devices with disparate functions. Current manufacturing methods such as those used in the semiconductor industry will not be economical at these scales; radically new approaches are needed. Moreover, for such products to be ubiquitous in the nation's future economy without creating long-term environmental or health hazards, these new approaches and the resulting products must be inherently sustainable by design.

A long-term vision for nanomanufacturing is to create flexible, "bottom-up" batch assembly methods that can be used to assemble elaborate systems of complex nanodevices. To create the foundation for achieving this vision, over the next decade this initiative will first establish industrial-scale manufacturing of functional systems with relatively limited complexity based on manufactured nanoparticles with designed properties. The organized assemblies of nanoparticles manufactured here will be designed to control and manipulate information, thermal energy, and electromagnetic radiation. The systems to be manufactured will include disruptive technologies for high-speed communication and computation, solar energy harvesting, waste heat management and recovery, and energy storage. The methods developed will be immediately extendable to more complex components and systems as future nanodevices mature.

Technical Program

Although the flexibility inherent in nanomaterials offers broad possibilities for future manufactured products, there are four requirements to move beyond one-off nanofabrication demonstrations to sustainable nanomanufacturing, as follows:

- Production must be scalable up to the required throughput and yield

[1] Please note that "collaborating agencies" is meant in the broadest sense and does not necessarily imply that agencies provide additional funds or incur obligation to do so. Agencies leading this effort and responsible for carrying out key aspects of these initiatives are underlined.

- The generation, manipulation, and organization of nanostructures must be accomplished in a precise, controlled, and environmentally responsible fashion
- All nanotechnology-based products must perform to specification over their expected lifetimes without the release of dangerous or harmful nanomaterials into the environment
- The bulk of the materials used must be recyclable with minimal waste or energy consumption

KEY THRUST AREAS: Three thrust areas in (1) materials design, (2) measurement technology, and (3) sustainable manufacturing will support product, tool, and process design informed by and adhering to the overall constraints of safety, scalability, and sustainability. The first thrust area focuses on scalable design of nanosystems and their manufacturing processes. The second thrust area drives new metrology for manufacturing nanoscale materials, components, and devices. The third thrust area develops reclamation and recycling processes for nanoscale devices and materials.

Thrust 1: *Design of scalable nanomaterials, components, and devices*

Nanomanufacturing relies on scaling up production from the laboratory demonstration level to true industrial volume production. This challenge must be addressed, in part, through nanomaterial, component, and device design that identifies and eliminates the fundamental limits to scaling. New scalable processes and techniques for generating and handling nanostructures safely and efficiently on an industrial scale must be developed, validated, and disseminated. Many of these techniques will have to rely on the self-assembly of nanostructures in order to cope with the vast numbers of nanocomponents needing to be assembled into complex systems. The success of this approach will depend on the careful design of individual nanostructures as well as on the development of new control methods designed to organize matter using predominantly stochastic rather than deterministic processes.

The research and development supported will specifically focus on overcoming the major technical barriers leading from the laboratory to the production line, including development of the following:

- Novel processes and techniques for scalable and sustainable manufacturing of known beneficial nanoscale materials, components, or devices, with preference given to processes applicable to broad classes of nanomaterials, components, and devices
- Novel beneficial nanomaterial components and devices produced by known scalable and sustainable manufacturing processes and techniques
- Fundamentals of nanomaterial, component, device, and/or nanomanufacturing process design specifically focused on scalability and sustainability

Thrust 2: *Nanomanufacturing measurement technologies*

The accuracy, precision, and reproducibility with which a structure can be manufactured are dictated in large part by the available metrology (i.e., “if it can’t be measured, it can’t be manufactured”). Measurement systems and standards have enabled industry to produce reliable goods and promote successful businesses and a healthy economy through high-quality process development. Nonetheless, the ability to tune and maintain nanoscale assembly processes is severely limited by the lack of truly nanoscale, real-time, in-line characterization techniques. The metrology tools required to quickly, inexpensively, and accurately characterize products at the relevant scales of one to hundreds of nanometers have yet to be developed. Existing methods are time-consuming, expensive, and require high-tech infrastructure and high skill levels to perform. For example, a clean-room laboratory infrastructure and advanced expertise are required to perform electron or atomic force microscopy and complex specimen preparation. Often, one must resort to macroscopic, and thus indirect, measurements of functionality that omit crucial information about the causal chain of process, structure, and function. In-line, fast, and inexpensive nanoscale metrology techniques must be developed to enable and maintain complex, multistep assembly processes in which a large number of variables have to be optimized and controlled.

Thrust 3: ***Recycling nanoscale materials, components, and devices***

The new manufacturing processes envisioned here will redefine the assembly line. Indeed, the ability to construct objects one nanoscale unit at a time suggests that nanomanufacturing facilities will have greater flexibility for tailoring processes to different products without costly retooling of assembly lines. This unmatched adaptability will increase profit margins and enable us to invent and evolve products according to the supply and demand of the day, and not limit what we can build to what a conventional manufacturing infrastructure may allow. Nonetheless, this versatility presents greater challenges for sustainability. While nanotechnology can be intrinsically “green” to the extent that it employs less material and smaller tools (e.g., microfluidics provide contained, controlled, high-yield manufacturing environments), the high surface-to-volume ratios of the materials, components, and devices produced by nanomanufacturing necessitate the development of novel processes for recovery and reclamation. New methods for recycling are required to promote human health and environmental sustainability of nanomanufacturing processes and nanomanufactured products.

Agency Roles and Contributions

The challenges of realizing a sustainable nanomanufacturing economy are significant, and our goals can only be met through a concerted interagency effort that addresses scientific and technological challenges spanning several disciplines.

Some of the most impressive examples of self-assembled complexity and functionality bridging nano- to macro-scales are in the biological world, and a critical challenge is to understand the basic principles that govern assembly in this realm (where NSF and NIH play key roles in this initiative), so that they can be adapted and applied to the high-throughput creation and integration of nanostructures (i.e., roles played by NSF, DOE, and NIST in this initiative). Similarly, basic scientific questions about the interplay of thermodynamics and kinetics in nanoscale assembly processes must be addressed to understand the fundamental physical limits of scalability and manufacturing error rates at nanometer scales (NSF, NIST, and DOE roles).

True nanomanufacturing, as distinct from one-off demonstrations, will require characterization and standardization that enable the use of nanomaterials and components as building blocks in quality-controlled industrial processes (NIST role). Environmental, health, and safety considerations must be integrated at all levels of research and development through regulation and through basic research into the toxicity and long-term environmental effects of new, active nanomaterials (EPA and NIH roles). Finally, the sustainability of manufacturing processes must be thoroughly understood from both scientific and practical standpoints (NIST, NSF, and DOE roles).

Table 1. Agency Contributions by Thrust Area

Thrust Area	**NIST**	**NSF**	**EPA**	**NIH**	**DOE**
1. Design of scalable nanomaterials, components, and devices	•	•		•	•
2. Nanomanufacturing measurement technologies	•	•		•	
3. Recycling nanomaterials, components, and devices		•	•		•

- **NIST:** Develop standards and best practices metrology procedures and tools for quantifying the relevant characteristics of nanomaterials and structures. (*Thrust Areas 1 and 2*)
- **NSF:** Develop fundamental science further to enable converting nanofabrication and nanoscale assembly processes into nanomanufacturing. (*Thrust Areas 1, 2, and 3*)
- **EPA:** Develop the requirements, rules, and procedures for the safe recycling and/or disposal of nanomaterials and structures. (*Thrust Area 3*)

- **NIH:** Develop fundamental science further to harness assembly in the biological world for nanomanufacturing without toxicity or harmful environmental effects. (*Thrust Areas 1 and 2*)
- **DOE:** Develop the processes and materials that enable energy efficiency in nanomanufacturing. (*Thrust Areas 1 and 3*)

Successful Outcomes

The metrics for success of this initiative are given by the milestones and timeframes shown below for each of the thrust areas. These broad sets of milestones serve as guidelines for each agency's contribution.

Thrust 1: *Design of scalable nanomaterials, components, and devices*

- 4-year – Demonstration of materials and processes that are scalable, efficient, and safe
- 8-year – Development of materials and processes with industrial partners to identify appropriate candidates for production and allow for effective technology transfer

Thrust 2: *Nanomanufacturing measurement technologies*

- 4-year – Demonstration of a suite of measurement systems satisfying the following criteria: fast, robust, standardized/traceable, real-time/in-line (e.g., for monitoring a production process continuously without stopping the process), and generic
- 8-year – Development and benchmarking of measurement systems and methodologies with industrial partners to allow transfer of measurement technology

Thrust 3: *Recycling nanoscale materials, components, and devices*

- 4-year – Identification and evaluation of recyclable/recoverable nanomaterials and processes for recovering/recycling them
- 8-year – Inclusion of recoverable/recyclable materials into scalable processes of Thrust Area 1

Bibliography

Chemical Industry Vision 2020 Technology Partnership. 2000. *Chemical Industry of the Future: Technology Roadmap for Materials*, http://www.chemicalvision2020.org/pdfs/materials_tech_roadmap.pdf.

———. 2003. *Chemical Industry R&D Roadmap for Nanomaterials by Design*, http://www.chemicalvision2020.org/pdfs/nano_roadmap.pdf.

———. 1998. *Workshop on Process Measurement and Control: Industry Needs*, http://www.chemicalvision2020.org/pdfs/workshop_processmanagement.pdf.

EPA. 2007. Nanotechnology White Paper, http://www.epa.gov/OSA/pdfs/nanotech/epa-nanotechnology-whitepaper-0207.pdf.

Max Planck Institute for Metals Research. 2009. GENNESYS White Paper, http://www.mf.mpg.de/mpg/websiteMetallforschung/english/veroeffentlichungen/GENNESYS/index.html.

National Science and Technology Council, Subcommittee on Nanoscale Science, Engineering, and Technology (NSET). 2006. *Instrumentation and Metrology for Nanotechnology: National Nanotechnology Initiative Workshop Report*, http://www.nano.gov/NNI_Instrumentation_Metrology_rpt.pdf.

NSET. 2007, *Manufacturing at the Nanoscale*: *National Nanotechnology Initiative Workshop Report*, http://www.nano.gov/NNI_Manufacturing_at_the_Nanoscale.pdf.